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ORIGINAL PAPER

Radiological study of the secondary reduction effect of early functional exercise on displaced intra-articular calcaneal fractures after internal compression fixation

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Abstract
Purpose Early post-operative exercise and weight-bearing activities are found to improve the functional recovery of patients with displaced intra-articular calcaneal fractures (DIACFs). We hypothesized that early functional exercise after surgery might have a secondary reduction effect on the subtalar joint, in particular the smaller fracture fragments that were not fixed firmly. A prospective study was conducted to verify this hypothesis.
Methods From December 2012 to September 2013, patients with unilateral DIACFs were enrolled and received a treatment consisting of percutaneous leverage and minimally invasive fixation. After surgery, patients in the study group started exercising on days two to three, using partial weight bearing starting week three, and full weight bearing starting week 12. Patients in the control group followed a conventional post-operative protocol of partial weight bearing after week six and full weight bearing after the bone healed. Computed tomography (CT) scanning was performed at post-operative day one, week four, week eight, and week 12 to reconstruct coronal, sagittal, and axial images, on which the maximal residual displacements of the fractures were measured. Function was evaluated using the American Orthopaedic Foot and Ankle Society (AOFAS) scoring scale at the 12th post-operative month.
Results Twenty-eight patients in the study group and 32 in the control group were followed up for more than 12 months; their data were collected and used for the final analysis. Repeated-measures analysis of variance (ANOVA) of the maximal residual displacements of the fracture measured on CT images revealed significant differences between the study and the control groups. There were interaction effects between group

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and time point. Except for the first time point, the differences between the groups at all studied time points were significant. In the study group, the differences between all studied time points were significant. Strong correlations were observed between the AOFAS score at post-operative month 12 and the maximal residual displacement of the fractures on the CT images at postoperative week 12.

Conclusions Early functional exercise and weight bearing activity can smooth and shape the subtalar joint and reduce the residual displacement of the articular surface, improving functional recovery of the affected foot. Therefore, early rehabilitation functional exercise can be recommended in clinical practice.

Keywords Displaced intra-articular calcaneal fractures · Early exercise · Early weight bearing · Secondary reduction effect · Computed tomography · Measurement

Abbreviations

DIACF displaced intra-articular calcaneal fracture
AOFAS American Orthopedic Foot and Ankle Society

Introduction

Calcaneal fracture comprises between 1% and 4% of all adult fractures [1, 2], and 60–80% are displaced intra-articular calcaneal fractures (DIACFs) [1–5]. DIACFs are complex and highly disabling injuries [6, 7]. Displacement of DIACFs as little as 1 or 2 mm can alter contact pressures on the subtalar joint and lead to post-traumatic arthritis [8, 9]. Therefore, it is important to restore the articular congruity of the subtalar joint for the most promising functional recovery of DIACFs [10]. DIACFs involving the posterior facet with more than 2 mm displacement or fracture dislocations should be treated surgically. Various operative techniques via an open approach or minimally invasive approach have been proposed for treating DIACFs [1, 11–22]. However, due to multiple factors, such as severe fracture damage (with comminuted fracture fragments), unique anatomical structure of the calcaneus, surgical experience of the surgeons, and constraints from reduction devices and fixation materials, some patients with DIACFs might experience incomplete anatomical reduction of the articular surface and ineffective fixation. As a result, these patients might experience post-operative local pain and traumatic arthritis of the subtalar joint over the long-term.

After surgical treatment for intra-articular calcaneal fractures, early exercise and weight bearing activities can improve the functional recovery of affected patients [17, 18, 23–26]. Through computed tomography (CT) during follow-up, a decreasing trend of the post-operative residual displacement in patients with DIACFs after internal fixation were observed [18, 26]. Immediate weight bearing after ankle fracture fixation has also been associated with better mobility, a shorter hospital stay, and an earlier return to work [27–29]. We deduced that early functional exercise after surgery might have a secondary reduction effect on the subtalar joint, in particular the smaller fracture fragments that have not been fixed firmly. Early smoothing and reshaping of the subtalar joint can further improve reduction performance, improving treatment efficacy.

To our knowledge, no studies using residual displacement measurements on CT images to quantify the secondary reduction effect of early functional exercise after surgery on the residual displacement of the articular surface have been reported. To confirm that early functional exercise after surgery has a secondary reduction effect through smoothing and shaping the subtalar joint and thus improves the treatment outcomes, we performed this prospective comparative imaging study. All included patients underwent internal fixation for DIACFs and received CT scans of the calcaneus during follow-up. Using CT, we examined the secondary reduction of the fracture fragments on the articular surface of the subtalar joint after early functional exercise and the functional recovery of the affected foot.

Methods

Patients

This study has been reviewed and approved by the Institutional Review Board (IRB) of the Third Hospital of Hebei Medical University. Starting from December of 2012, patients with DIACFs who were admitted to and treated in our department were enrolled in this study. The inclusion criteria were as follows: (1) patients with unilateral closed intra-articular calcaneal fractures; (2) Sanders II, III, or IV fractures confirmed by CT examination; (3) patients who accepted and followed a postoperative functional exercise plan designated using a random number table; and (4) patients who were followed up for more than 12 months. The exclusion criteria were as follows: (1) patients with bone fractures at other sites of the ipsilateral lower extremity; (2) patients whose fractures were accompanied by injuries of vital organs; (3) patients who also had a craniocerebral injury and experienced a loss of consciousness after being injured; (4) patients who also had severe internal medical disease; (5) patients who had a disordered or traumatized spine or an ischemic and necrotic femoral head that affected the function of the ipsilateral lower extremity; and (6) patients who could not walk normally due to congenital skeletal malformations of the lower extremities. Using a random number table, the patients who met all of the inclusion criteria and who agreed to participate in this study were randomly divided into a study group and a control group. After surgery, patients in the study group conducted early functional exercise according to the pre-designed plan, and patients in the control group conducted functional exercise following a conventional plan.

Lateral and axial X-ray films of the calcaneus were taken, and the Böhler's angle and Gissane angle were measured on the lateral X-ray films. The ipsilateral calcaneal CT scans were conducted, and the axial, coronal, and sagittal CT images of the affected calcaneus were reconstructed. The severity of the fracture was assessed in accordance with the Sanders classification system. Patients underwent surgery once the swelling diminished and the local skin was wrinkled. The DIACFs were treated using a minimally invasive technique [16–18, 26, 30], which features percutaneous leverage reduction using two Kirschner wires and fixation with an anatomic plate and some compression bolts (Shandong Wego Orthopedic Device Co., Ltd., Weihai, China) via a small longitudinal lateral incision made on the hind foot (Fig. 1) with the aim of reducing wound complication rate and promoting functional recovery.

Post-operative management and follow-up

Patients in the study group were encouraged to exercise early after surgery: these individuals started active exercise of the ipsilateral ankle, subtalar joint and toes once the pain became tolerable. The amplitude and frequency of exercise were increased gradually. At post-operative days two to three, patients were encouraged to get out of bed and perform non-weight-bearing exercises with crutches. At postoperative day three, patients were instructed to roll a cylindrical bottle placed beneath the sole of the foot back and forth to promote joint reshaping. Weight bearing was started at post-operative week three. At first, the affected foot continuously bore a weight of 5 kg for at least 30 minutes every day for early smoothing and shaping the subtalar joint. Afterwards, the weight was increased, and the weight bearing duration was gradually prolonged. Full weight bearing was started at post-operative week 12. Patients in the control group performed functional exercise according to a conventional plan [31]. At post-operative week two, active motion of the ankle and subtalar joint started if the wound healed well without complications. Patients learned to draw the alphabet with the hallux of the injured foot or make progressively larger circles with the feet. Partial weight bearing was started at post-operative week six, and full weight bearing was allowed after the healing of the bone fracture was confirmed using radiography, usually after post-operative week 12.

Patients were followed up and they received CT scans (1.0 mm section thickness) of the ipsilateral calcaneus at post-operative day one, week four, week eight, and week 12. Continuous CT images on the coronal, sagittal, and axial planes were analyzed to determine the residual step-off on the posterior articular surface of the calcaneus and to identify the location of the maximal step-off. The selected CT views showing the maximal residual displacement were magnified five to ten times. Then the maximal values of the residual displacements were measured three times (by author BL)

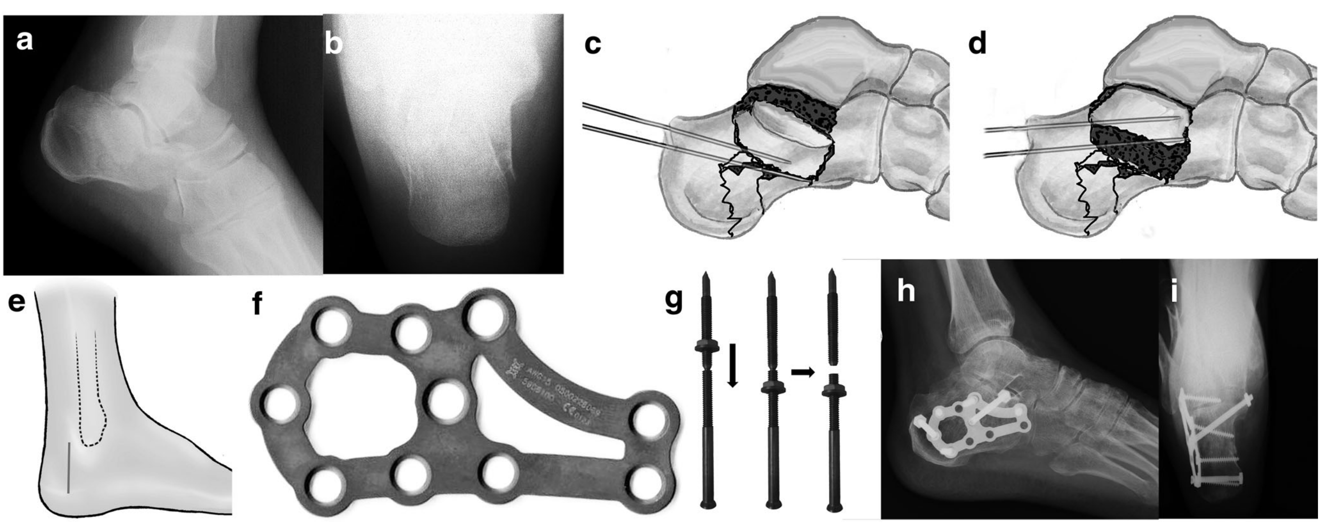

Fig. 1 A 33-year old male in the study group sustained displaced intra-articular calcaneal fractures of the right foot as shown on the lateral (**a**) and axial radiographs (**b**). Two Steinmann pins are introduced beneath or in the major fracture fragment (**c**), and percutaneous leverage is performed to reduce the major fracture fragment (**d**). A small longitudinal posterior incision is made on the lateral side of the hindfoot (**e**), subsequently with a subcutaneous tunnel created by using a periosteal elevator. The anatomical plate is inserted percutaneously into the subcutaneous tunnel (**f**). The compression bolts (**g**) consist of nuts and screws with constricted area (*arrow*). The nut is used to fasten the screw to generate enormous compression force to restore the width and height of calcaneus to the utmost degree, and the part of the screw lateral to the constricted area is broken off. The postoperative radiographs showed nearly anatomical reduction and rigid fixation (**h**, lateral view; **i**, axial view)

using the SIEMENS syngo 2012D measurement tool originally installed in the SIEMENS CT system, and the average value was calculated and recorded for further analysis. After a two-year interval, BL and another author HL were asked to select the sagittal, axial and coronal CT images showing the maximal residual step-offs of the articular facet and re-measure the residual step-offs independently.

At postoperative month six, month 12, and once every six months thereafter, patients were followed up and underwent radiographic examinations. A senior surgeon who was blinded to the study design and patient grouping assessed the foot functional recovery of patients according to the American Orthopedic Foot and Ankle Society Ankle-Hindfoot Scale (AOFAS) [32, 33].

Data analysis

SPSS 21.0 software (SPSS, Chicago, IL, USA) was used for statistical analysis. Normally distributed measurement data were analyzed using t tests, and non-normally distributed continuous variables were analyzed using Mann-Whitney *U* tests. Enumeration data were analyzed using chi-squared tests. Repeated-measures analysis of variance (ANOVA) was applied to analyze the repeated measurements. For variables that showed an interaction effect, the individual effects were further analyzed. Bonferroni corrections were used for post-hoc analysis of multiple comparisons. Correlation analysis of non-normally distributed measurement data was performed using Spearman rank correlation tests, and Cohen's method [34] was applied to compare correlation coefficients. Intra- and interclass correlation coefficient test was performed to investigate the measurement reliability. A *P*-value less than 0.05 indicated a statistically significant difference.

Results

From December 2012 to September 2013, 382 patients with DIACFs were admitted to and treated in our department, 72 of whom met the inclusion criteria and provided informed consent to participate in this study. According to the number randomly designated at the time of admission, 37 patients were included in the study group and 35 in the control group. Five patients dropped out during the follow-up period, including four patients in the study group who could not follow the plan for post-operative rehabilitation exercise and one patient in the control group who dropped out owing to personal reasons. After surgery, excluding the seven patients who were lost to follow-up, 60 patients were followed up for more than 12 months (28 in the study group and 32 in the control group), and their follow-up data were used for the final analysis.

There were no significant differences in age, sex, severity of calcaneal fracture (using Sanders classification), Böhler's angle, Gissane angle, time from injury to operation, or operation time between the study group and the control group (Table 1). All patients were followed up and received CT scans of the ipsilateral calcaneus at postoperative day one, week four, week eight, and week 12 (Figs. 2, 3, 4 and 5). The maximal residual displacement of the subtalar joints were identified and measured on the sagittal, axial and coronal CT planes twice by BL with a 24-month interval (in 2015 and 2017, respectively) and once by HL (in 2017) independently. The intra- and interclass correlation coefficient (ICC) tests were performed (Table 2 and Supplementary Table 1), which revealed high measurement reliability following the method described above. Therefore, the maximal residual displacement measured on the coronal, sagittal, and axial planes by BL in 2015 were used for further analysis (Table 3).

Table 1 General information of patients in both the study and the control groups

General information	Study group (N = 28)	Control group (N = 32)	Statistics	P-value
Age (years)	40.3 ± 12.6	38.7 ± 11.5	$t = 0.514$	0.609
Sex			$\chi 2 = 0.054$	0.817
Male	23	27		
Female	5	5		
Sanders classification			$\chi 2 = 0.636$	0.727
Type II	9	10		
Type III	8	12		
Type IV	11	10		
Böhler's angle	5.7 ± 11.6	4.5 ± 10.8	$t = -0.381$	0.705
Gissane angle	86.2 ± 19.3	77.5 ± 17.9	$t = 1.811$	0.075
Time from injury to operation (days)	7.3 ± 1.9	6.8 ± 1.7	$t = 1.076$	0.286
Operative time (min)	64.5 ± 17.1	61.6 ± 20.3	$t = 0.594$	0.555

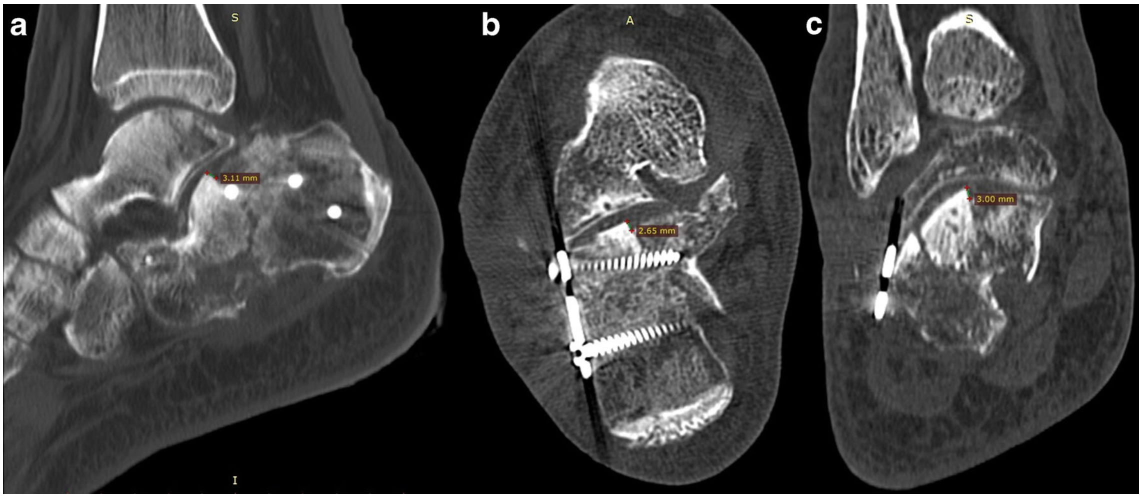

Fig. 2 Measurement of the maximal residual displacement of calcaneal fracture on the CT sagittal (**a**), axial (**b**) and coronal (**c**) images taken at postoperative day 1 (The same patient as shown in Fig. 1)

For the measurements obtained from the sagittal CT images, repeated-measures ANOVA (Supplementary Table 2) revealed significant differences between the groups (F = 6.590, $P = 0.013$) and between different time points (F = 132.032, $P < 0.001$), as well as an interaction effect between group and time point (F = 8.227, $P < 0.001$). Further analysis of individual effects showed significant inter-group differences at the other time points ($P < 0.05$) except for the first time point ($P > 0.05$). In both the control group and the study group, the differences between time points were significant (both $P < 0.05$), and the residual displacement of the fracture at the sagittal plane gradually decreased over time.

Repeated-measures ANOVA (Supplementary Table 3) of the data obtained from the axial CT images revealed significant differences between the groups (F = 10.138, $P = 0.002$) and between different time points (F = 92.874, $P < 0.001$), in addition to an interaction effect between the groups and time points (F = 5.168, $P = 0.005$). Further analysis of individual effects showed that, except for the first time point ($P > 0.05$), the inter-group differences at the other time points were significant ($P < 0.05$). In both the control group ($P < 0.05$) and the study group ($P < 0.0.05$), the differences between time points were significant, and the residual displacement of the fracture at the axial plane gradually decreased over time.

For the measurements obtained from the coronal CT images, repeated-measures ANOVA (Supplementary Table 4) revealed significant differences between the groups ($F = 6.567$, $P = 0.013$) and between different time points (F = 122.548, $P < 0.001$), as well as an interaction effect between the groups and time points (F = 11.849, $P < 0.001$). Further analysis of individual effects showed significant inter-

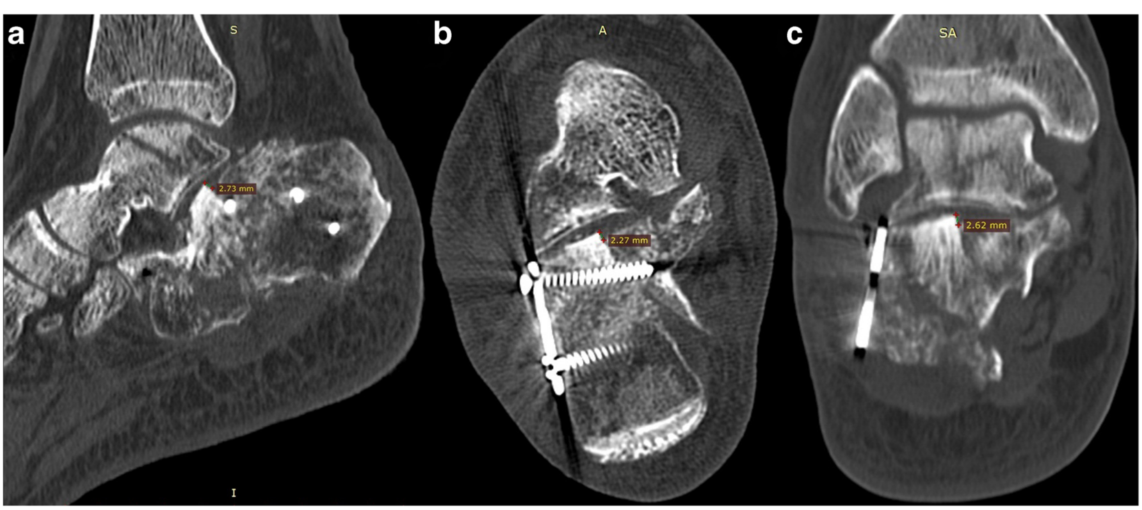

Fig. 3 Measurement of the maximal residual displacement of calcaneal fracture on the CT sagittal (**a**), axial (**b**) and coronal (**c**) images taken at postoperative week 4 (The same patient as shown in Fig. 1)

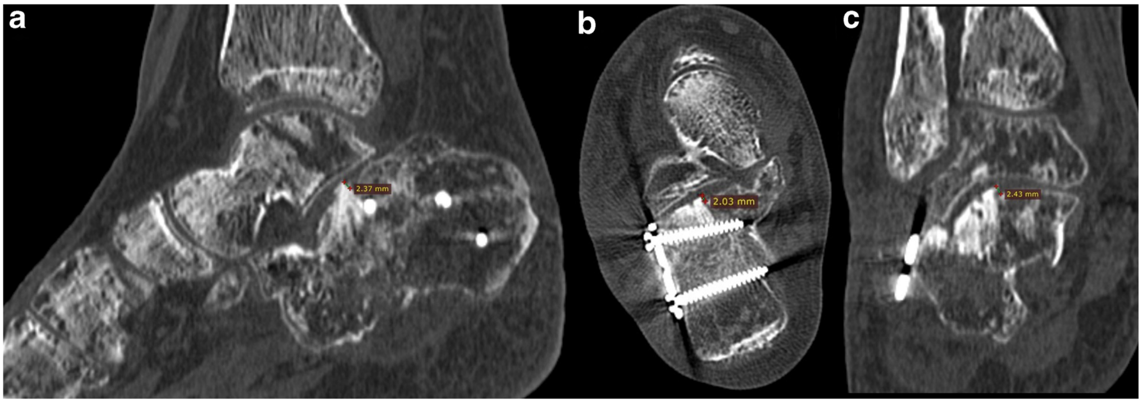

Fig. 4 Measurement of the maximal residual displacement of calcaneal fracture on the CT sagittal (**a**), axial (**b**) and coronal (**c**) images taken at post-operative week 8 (The same patient as shown in Fig. 1)

group differences at all time points ($P < 0.05$) except for the first time point ($P > 0.05$). In the control group, except for a non-significant difference observed between week eight and week 12, the differences between the other time points were all significant ($P < 0.05$). In the study group, the differences between all the time points were significant ($P < 0.05$), and the residual displacement of the fracture at the coronal plane gradually decreased over time.

At the post-operative month 12 follow-up, the AOFAS score was 88.7 ± 7.6 for the study group and 81.4 ± 11.5 for the control group ($t = 2.920$, $P = 0.003$). The Böhler's angle and Gissane angle measured on the lateral X-ray films of the calcaneus were 33.1 ± 8.7 degrees and 118.0 ± 11.5 degrees, respectively, in the study group, and 31.4 ± 10.0 degrees and 121.6 ± 13.4 degrees, respectively, in the control group. The differences in both angles were not significant between the groups ($t = 0.697$, $P = 0.224$; $t = 1.117$, $P = 0.134$, respectively).

Spearman rank correlation tests were applied to analyze the correlations of the AOFAS score at post-operative Month 12 with the maximal residual displacement of the fracture at post-operative Week 12 measured from the reconstructed coronal, sagittal, and axial CT images, as well as with the Böhler's angle and the Gissane angle. Correlation coefficients were compared using the method proposed by Cohen [34]. From the reconstructed CT images taken at postoperative Week 12, comparison of the correlation coefficients between the maximal residual displacements of the fracture at different planes with AOFAS scores showed significant inter-group differences ($P < 0.001$). In terms of the correlation with AOFAS scores, the order from high to low was sagittal displacement (rs = 0.998), coronal displacement (rs = 0.779), and axial displacement (rs = 0.468). No significant inter-group differences in the correlation coefficients of the Böhler's and Gissane angles with the AOFAS scores were detected ($P = 0.662$, $P = 0.167$).

Two patients had a superficial infection of the post-operative wound: one patient each in the study and control groups. One patient in the study group had sural nerve injury. Four patients had medial plantar nerve injury and activity limitations of the flexor pollicis longus muscle, one in the study group and three in the control group. All patients underwent the removal of internal fixation materials, which was conducted at post-operative month five in two patients

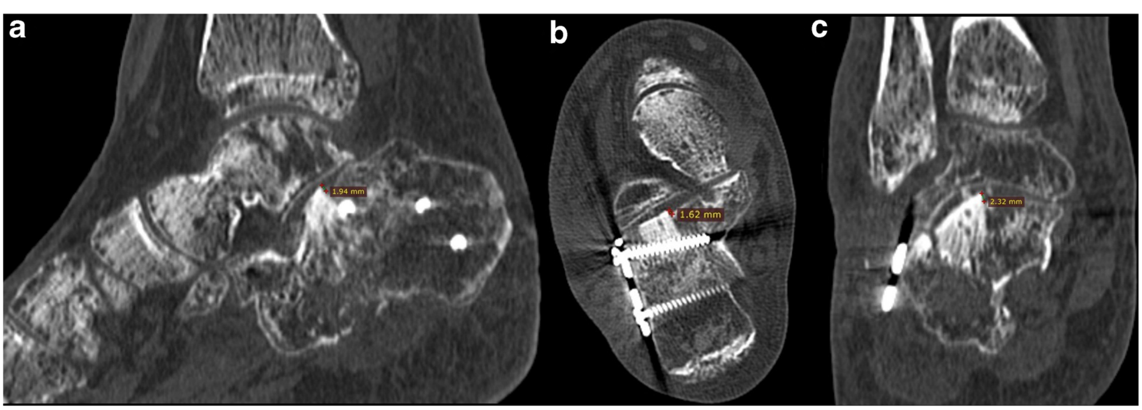

Fig. 5 Measurement of the maximal residual displacement of calcaneal fracture on the CT sagittal (**a**), axial (**b**) and coronal (**c**) images taken at post-operative week 12 (The same patient as shown in Fig. 1)

Table 2 The maximal residual displacement of the subtalar joints were identified and measured on the sagittal, axial and coronal CT planes twice by BL with a 24-month interval (in 2015 and 2017, respectively). The intraclass correlation coefficient (ICC) test was performed

Measurement of the maximal residual displacement (mm)	Sagittal plane		Axial plane		Coronal plane	
	Control group	Study group	Control group	Study group	Control group	Study group
Measurement in 2015	1.91 ± 0.72	1.52 ± 0.70	2.41 ± 0.85	1.88 ± 0.79	1.91 ± 0.71	1.53 ± 0.71
Measurement in 2017	1.95 ± 0.70	1.49 ± 0.67	2.44 ± 0.81	1.84 ± 0.81	1.78 ± 0.72	1.59 ± 0.70
ICC	0.983	0.890	0.992	0.930	0.889	0.989
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

(one in each group) owing to medial plantar nerve injury and activity limitations of the flexor pollicis longus muscle and at post-operative months 12–18 in the other 58 patients.

Discussion

There have been advancements in surgical technologies, internal fixation materials and improvements in radiological support. However, patients with DIACF, treated using open reduction and internal fixation via the extended L-approach or percutaneous reduction, and internal fixation via various minimally invasive approaches, still face the risks of subtalar joint malreduction and resulting poor treatment outcomes that can occur due to the unique anatomical structure of the calcaneus and the complexity of calcaneal fractures [35, 36]. Thus, improvement of the facet residual displacement and treatment outcomes after surgical treatment for DIACFs is still of a great concern to orthopaedists. Early functional exercise after surgery is a potentially effective approach.

The appropriateness of early exercise after the surgical treatment of DIACFs is still controversial. Schepers et al. reported that non-weight-bearing exercise started on average nine weeks after open reduction and internal fixation of calcaneal fractures in the Netherlands [37]. Paul et al. believed that a long period of non-weight-bearing after surgery might result in a highly fragile and sensitive calcaneus along with the surrounding soft tissue of the heel, and thus, early weight bearing was recommended [23, 38]. Redfern et al. stated that, after using a locking plate to firmly fix the fractured calcaneus, early weight bearing excise after surgery could be conducted without adverse effects on fracture stability [38, 39]. In previous studies, the follow-up observation confirmed satisfactory treatment efficacy in the patients with DIACFs who were encouraged to start early postoperative functional exercise and weight bearing [17, 18, 23–26]. In addition, CT scans taken during follow-up revealed a decreasing trend of the postoperative residual displacement of the fracture. We deduced that early functional exercise after surgery might have a secondary reduction effect on the subtalar joint by smoothing and shaping the joint, thereby improving treatment outcomes. However, in previous studies, quantitative measurement of the postoperative facet residual displacement using radiological methods were not conducted, nor were the correlations between the facet residual displacement and hindfoot functional recovery investigated. A literature search showed that no related studies have been reported previously. Therefore, we conducted this prospective radiological study.

In this study, the included patients with a unilateral DIACF received treatment consisting of fracture reduction with percutaneous leverage, placement of a calcaneal anatomical plate through a small longitudinal lateral incision on the hind foot, and internal fixation with compression bolts. Patients in the study group started functional exercise early after surgery, including rolling a bottle beneath the sole of the foot to smooth and reshape the subtalar joint starting at post-operative days two to three, partial weight bearing starting at post-operative week three, and full weight bearing starting at post-operative week 12. Patients in the control group began partial weight bearing at post-operative week six and full weight bearing

Table 3 The residual maximal displacement of calcaneal fractures after fixation measured on the sagittal, axial, and coronal CT scan images taken at day 1 and weeks 4, 8, and 12 postoperatively

Time	Control group (mm)			Study group (mm)		
	Sagittal plane	Axial plane	Coronal plane	Sagittal plane	Axial plane	Coronal plane
Day 1	2.26 ± 0.73	2.81 ± 0.8	2.25 ± 0.72	2.14 ± 0.72	2.56 ± 0.72	2.20 ± 0.77
Week 4	2.03 ± 0.70	2.59 ± 0.83	2.05 ± 0.70	1.59 ± 0.51	2.03 ± 0.67	1.64 ± 0.52
Week 8	1.76 ± 0.70	2.23 ± 0.73	1.72 ± 0.60	1.31 ± 0.56	1.66 ± 0.62	1.31 ± 0.48
Week 12	1.59 ± 0.60	2.01 ± 0.72	1.62 ± 0.66	1.02 ± 0.46	1.25 ± 0.46	0.97 ± 0.38

after the fracture healed. All patients received CT scans of the ipsilateral calcaneus at post-operative day one, week four, week eight, and week 12. The maximal residual displacement of the fracture was measured on the coronal, sagittal and axial CT images. Statistical analysis was conducted to compare the maximal residual displacements in different planes and at different time points between the study and control groups. The results showed that the differences between the groups and between different time points were all significant. Compared to the control group, early exercise after surgery led to a significantly more effective reduction in the maximal residual displacement of the posterior articular surface of the subtalar joint, indicating that early functional exercise and weight bearing after surgery had a remarkable secondary reduction effect on the articular surface residual displacement. Spearman rank correlation tests revealed strong correlations between the AOFAS score at postoperative month 12 and the maximal residual displacements of the fractures at postoperative week 12 as measured on the coronal, sagittal and axial CT images. In particular, the maximal residual displacements of the fractures measured from the sagittal images demonstrated the most significant correlation with the AOFAS scores. However, no significant differences in the correlation coefficients of the Böhler's and Gissane angles with the AOFAS scores were detected between the groups.

The limitations of this study are as follows. First, the sample size was relatively small. A larger number of patients who meet the inclusion criteria will be included for radiological measurement and follow-up in our subsequent studies. Second, we only explored the effects of early functional exercise and weight bearing on the displacement of the articular surface of the calcaneus, but not on the local soft tissue. Satisfactory recovery of soft tissue can further facilitate the restoration of foot function. Therefore, in future studies, we will investigate the effect of early rehabilitation exercise on both the bony structure and the surrounding soft tissue of the calcaneus. Third, the reconstructed CT images are not exactly the same at different follow-up points, and a slight change in the reconstructed CT planes may affect the measurement of the residual facet displacement. Comprehensive studies in the future can further deepen our understanding of the factors influencing functional recovery after internal fixation for DIACFs, with the hope of developing a more scientific and suitable treatment and rehabilitation strategy.

Conclusions

Early rehabilitation exercise after minimally invasive reduction and internal fixation treatment for DIACFs is recommended. Early functional exercise and weight bearing can smooth and reshape the subtalar joint and reduce the fracture residual displacement of the articular surface, promoting functional recovery of the affected foot.

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Compliance with ethical standards

Conflict of interest statement This study was supported by the National Natural Science Foundation of China (Grant No. 81401789) and the Top Young Talents for Hebei Province (2013–2015). The funding sources have no role in study design, conduction, data collection, or statistical analysis. On behalf of all authors, the corresponding author states that there is no other conflict of interest.

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